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Marginal adaptation, fracture load and macroscopic failure mode of adhesively luted PMMA-based CAD/CAM inlays

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Abstract: OBJECTIVES To evaluate marginal adaptation, fracture load and failure types of CAD/CAM polymeric inlays. METHODS Standardized prepared human molars (48) were divided into four groups (n=12): (A) PCG (positive control group); adhesively luted glass-ceramic inlays, (B) TRX; CAD/CAM polymeric inlays luted using a self-adhesive resin cement, (C) TAC; CAD/CAM polymeric inlays luted using a conventional resin cement, and (D) NCG (negative control group); direct-filled resin-based composite restorations. All specimens were subjected to a chewing simulator. Before and after chewing fatigue, marginal adaptation was assessed at two interfaces: (1) between dental hard tissues and luting cement and (2) between luting cement and restoration. Thereafter, the specimens were loaded and the fracture loads, as well as the failure types, were determined. The data were analysed using three- and one-way ANOVA with post hoc Scheffé test, two sample Student's t-test ($p<0.05$). RESULTS Before and after chewing fatigue, marginal adaptation for interface 1 showed significantly better results for TRX and PCG than for TAC (p=0.001-0.02) and NCG (p=0.001-0.047). For interface 2, marginal adaptation for TAC was significantly inferior to TRX ($p<0.001$) and PCG ($p<0.001$). Chewing fatigue had a negative impact on the marginal adaptation of TAC and NCG. No significant differences in fracture load were found between all tested groups. SIGNIFICANCE Self-adhesive luted polymeric CAD/CAM inlays showed similar marginal adaptation and fracture load values compared to adhesively luted glass-ceramic inlays.

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Marginal adaptation, fracture load and failure analyses of adhesively luted PMMA-based CAD/CAM inlays

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Abstract

Objectives: To evaluate marginal adaptation, fracture load and failure types of CAD/CAM polymeric inlays.

Methods: Standardised prepared human molars (48) were divided into four groups (n = 12): A) PCG (positive control group); adhesively luted glass-ceramic inlays, B) TRX; CAD/CAM polymeric inlays luted using a self-adhesive resin cement, C) TAC; CAD/CAM polymeric inlays luted using a conventional resin cement, and D) NCG (negative control group); direct-filled resin-based composite restorations. All specimens were subjected to a chewing simulator. Before and after chewing fatigue, marginal adaptation was assessed at two interfaces: 1) between dental hard tissues and luting cement and 2) between luting cement and restoration. Thereafter, the specimens were loaded and the fracture loads, as well as the failure types, were determined. The data were analysed using three- and one-way ANOVA with post-hoc Scheffé test, two sample Student's t-test and Weibull statistics ($p < 0.05$).

Results: Before and after chewing fatigue, marginal adaptation for interface 1 showed significantly better results for TRX and PCG than for TAC ($p = 0.001 - 0.02$) and NCG ($p = 0.001 - 0.047$). For interface 2, marginal adaptation for TAC was significantly inferior to TRX ($p < 0.001$) and PCG ($p < 0.001$). Chewing fatigue had a negative impact on the marginal adaptation of TAC and NCG. No significant differences in fracture load were found between all tested groups. Group TAC showed the highest Weibull moduli ($m = 4.49$) and group PCG the lowest ($m = 2.78$).

Significance: Self-adhesive luted polymeric CAD/CAM inlays showed similar marginal adaptation and fracture load values compared to adhesively luted glass-ceramic inlays.

Key words: polymeric material, CAD/CAM, inlays, CEREC, fracture load, marginal adaption

1. Introduction

The choice of whether polymer or ceramic material is the best for tooth coloured CAD/CAM inlay restorations has already been the topic of deliberations during development and introduction of the first clinically applicable CAD/CAM system in 1985 [1, 2]. Using material blocks which are prefabricated under controlled conditions by the manufacturer, CAD/CAM offers the chance to use materials at their highest obtainable quality, assuming that the material is not weakened by the automatic machining process. The concept of bonded aesthetic ceramic CAD/CAM inlays has been successfully established through clinical long-term studies [3, 4]. Today, as an alternative to aesthetic silicate ceramics, composite and PMMA blocks have been introduced for CAD/CAM dental reconstructions [5-8]. The CAD/CAM resin blocks are cured under high pressure and temperature and therefore yield higher mechanical properties compared to conventionally polymerised resins [5, 7, 8]. One study of CAD/CAM three-unit polymeric fixed partial dentures (FPDs) observed significantly higher fracture load results compared to glass-ceramics, as well as conventionally polymerised resins, after different aging regimens [8]. In several studies, CAD/CAM fabricated composite overlays and crowns for premolars and molars showed high fatigue resistance and were recommended for long-term reconstructions [9-11].

Fasbinder et al. [12] investigated the clinical performance of CAD/CAM fabricated resin-based composite inlays and observed that their colour match with natural teeth was significantly better than that of glass-ceramic CAD/CAM inlays after three years. One *in vitro* study observed no differences in colour stability between CAD/CAM polymeric and glass-ceramic FPDs [13]. Lehmann et al. [14] evaluated clinical failures, the presence of occlusal contacts, plaque accumulation and the patients' ratings of the aesthetics and functional efficiency of 114 composite single crowns for five years. They concluded that their complication rate and the increased plaque accumulation restrict the indication of composite crowns to temporary, or at most semi-permanent, use.

To the best of our knowledge, at present, there is no information available on the fracture load of molars restored with adhesively luted PMMA-based CAD/CAM inlays, whereas fracture load and marginal adaptation of CAD/CAM ceramic inlays has been investigated under various conditions in recent studies [15-17]. The first steps in evaluating whether unfilled PMMA-based CAD/CAM block material may be suitable to be used for permanent occlusion bearing molar inlays should assess marginal integrity after mechanical loading and thermal stressing by a chewing fatigue test [18]. This is because the elastic and thermal expansion properties of polymers differ significantly from those of the natural dental hard tissues, as well as from those of aesthetic silicate ceramics, which represent the standard CAD/CAM inlay material [19-23]. The physical and chemical properties of PMMA-based FPDs also raise the question of whether adequate adhesion can be established between the polymer and current cementation systems and how resistant it may be to thermal and mechanical stress. Conventional resin cement systems and self-etch resin cements represent the current standard of adhesively seating inlays and are expected to durably restore the stability of the restoration-tooth system [24-26]. Testing marginal adaptation of class II-restorations seated in natural extracted molars with a chewing fatigue test is considered to provide useful information on the integrity of the type of restoration [16, 27-29].

The aim of this study was to evaluate marginal adaptation and fracture load of PMMA-based CAD/CAM inlays. The null-hypotheses tested were whether marginal adaptation and fracture load of PMMA-based CAD/CAM inlays would be similar to that of glass-ceramic inlays and direct resin-based composite fillings.

2. Material and methods

2.1 Preparation of specimens

For this *in vitro* study, 48 extracted caries-free molars were collected, cleaned from periodontal tissue residues and stored in 0.5 % chloramine T at room temperature for one week [30]. Subsequently, the teeth were embedded with their roots parallel to the tooth axis in autopolymerising resin (Palapress, Heraeus Kulzer, Hanau, Germany) using a special holding device. Non-bevelled mesio-occlusal-distal (MOD) class II-cavities were prepared with similar dimensions under constant water-cooling (Figure 1). Initially, an 80 µm diamond bur (No. 8422, Intensiv SA, Grancia, Switzerland) was used for preparation, and a 25 µm diamond bur (No. 3526, Intensiv SA) of the same size and form was used for finishing at 12x magnification (Stemi 1000, Carl Zeiss AG, Oberkochen, Germany). The proximal boxes ended mesially 1 mm above and distally 1 mm below the cemento-enamel junction. After preparation, the teeth were randomly assigned to four groups (n = 12 per group):

- **A)** PCG, positive control group: Teeth restored with glass-ceramic CAD/CAM inlays (Empress CAD, Ivoclar Vivadent, Schaan, Liechtenstein) luted using a conventional resin cement (Variolink II, Ivoclar Vivadent)
- **B)** TRX: Teeth restored with unfilled PMMA-based CAD/CAM inlays (artBloc Temp, Merz Dental, Lütjenburg, Germany) luted using a self-adhesive resin cement (RelyX Unicem, 3M ESPE, Seefeld, Germany)
- **C)** TAC: Teeth restored with unfilled PMMA-based CAD/CAM inlays (artBloc Temp) luted using a conventional resin cement (artCem GI, Merz Dental)
- **D)** NCG: Negative control group, teeth directly filled with resin-based composite (Filtek Supreme XT, 3M ESPE, Seefeld, Germany)

For manufacturing of the CAD/CAM inlays, the teeth were scanned with a CEREC 3D camera (Sirona, Bensheim, Germany). The inlays were designed by CAD/CAM Software (inLab 3D, Program Version 3.65, Sirona) and milled (InLab MC XL milling machine, Sirona). Subsequently, the cementation surface of the resin inlays were air-abraded with alumina powder with a mean particle size of 50 µm (LEMAT NT4, Wassermann, Hamburg, Germany) for 10 s at a pressure of 2 bar and at a distance of 10 mm between the nozzle and the polymeric inlay surface [6].

Thereafter, all CAD/CAM inlays were luted according to the manufacturers' instructions (Table 1). NCG teeth received a 0.5 mm enamel bevel and were filled with resin-based composite using an incremental filling technique [29]. Subsequently, the interfaces between inlay and the cavity margins were finished with 15 µm diamond burs (No. 4274, Intensiv SA) under continuous water-cooling. Inlays were polished with Sof-Lex discs (3M ESPE) of descending roughness for 60 s. Finishing was done with an occlubrush polisher (Kerr, Bioggio, Switzerland) and a diamond polishing paste (Vita Karat, Vita Zahnfabrik, Bad Säckingen, Germany) [31].

2.2. Marginal adaptation measurements

Three replicas (occlusal, mesial and distal) of each tooth were taken before (initial) and after (terminal) the chewing fatigue test using an autopolymerising resin (PalaXpress, Heraeus Kulzer, Hanau, Germany). The replicas were sputter coated with gold (Sputter SCD 030, Balzers Union, Balzers, Liechtenstein). Marginal adaptation was measured [32] before and after chewing fatigue using a SEM (Amray 1810/T, Amray, Bedford; MA, USA) at 200x magnification. The SEM investigator was blinded with respect to the assignment of the specimens and to the respective groups. Evaluation of marginal integrity was performed at two interfaces; interface 1: between dental hard tissues and the luting resin cement; interface 2: between luting resin cement and reconstruction. All specimens were examined for “continuous” margins (no gap, no interruption of continuity) and discontinuous “imperfect” margins (gap due to adhesive or cohesive failure; or fracture of restorative materials; or fracture of enamel related to restoration margins) [32].

2.3. Chewing fatigue test of specimens

The chewing fatigue test was performed using a simulator (custom-made device at the University of Zurich) [18]. The specimens were mechanically loaded 1.2 million times at a force of 49 N and frequency of 1.67 Hz. Simultaneous thermal cycles were achieved by changing the surrounding water temperature in the chamber every 120 s from 5 °C to 50 °C. In total, the temperature changed 6,000 times during the occlusal loading. For preparation of antagonists, palatal cusps of caries-free human maxillary second molars were separated, embedded in amalgam (Dispersalloy, Dentsply, Konstanz, Germany) and fixed onto a carrier [18]. The antagonists were stored in water during the whole experiment to avoid desiccation.

2.4. Fracture load measurements

After the marginal adaptation measurements, the specimens were loaded in the universal testing machine (cross-head speed: 1 mm/min, Zwick/Roell Z010, Zwick, Ulm, Germany). The load was induced with a steel ball (diameter: 12 mm) on the reconstruction on the inner side of the cusp to the long axis of the tooth (Figure 1a). To achieve even force distribution, a 0.5 mm tin foil (Dentaurum, Ispringen, Germany) was placed between the teeth and the loading steel ball. The fracture load was registered as soon as fracture load decreased by 10 % of the maximum load (Fmax).

2.5. Failure analysis

Five fracture types were observed: tooth fracture (1), inlay fracture (2), fracture along margin (3), cusp fracture (4) and severe fracture (5) (Figure 1c). The fracture types were assessed by two independently operators under an optical microscope (x25, M3M, Wild, Heerbrugg, Switzerland).

2.6. Statistical analysis

Initially, descriptive statistics for marginal adaptation and fracture load were calculated. Three-way ANOVA for the marginal adaptation values with respect to test group, measured interface and chewing fatigue was conducted. Due to the significant three-way interaction ($p < 0.001$), one-way ANOVA with respect to the test group, followed by Scheffé post-hoc test, was applied before or after chewing fatigue and for measurements of interface “one” or “two” separately. Additionally, one-way ANOVA was used for the analysis of fracture load, followed by post-hoc Scheffé test, to evaluate the statistical differences between the test groups. Furthermore, the influence of chewing fatigue on marginal adaptation for each test group was calculated and compared by a two sample Student’s t-Test. In addition, under assumption of the underlying Weibull distribution, the least squares estimates of the modulus and characteristic fracture load were calculated according to the mean rank plotting [33]. The data were analysed using the statistical software program SPSS 19 (IBM, New York, NY, USA). In all tests, p-values less than 5 % were considered as statistically significant.

After the fracture load test, the failure types were classified in five modes and the relative frequencies of fracture types were calculated at 95 % confidence intervals [34].

3. Results

3.1 Marginal adaptation

The descriptive statistics (mean, SD, 95 % CI) of the marginal adaptation of all tested groups are summarised in Table 2 and presented in Figure 2. The three-way interaction (test group vs. chewing fatigue vs. interface) was significant ($p < 0.001$). Additionally, the interactions between test group vs. interface vs. chewing fatigue showed a significant impact ($p = 0.036$). Therefore, the fixed effects test group, chewing fatigue and interface cannot be compared directly as the higher order interactions were found to be significant. Consequently, several difference analyses are provided splitting at the level of test groups, chewing fatigue and interface factors, depending on the hypothesis of interest.

Before and after chewing fatigue, marginal adaptation for the interface between dental hard tissue and luting resin cement showed comparable results between self-adhesive resin combined with polymeric CAD/CAM inlays (TRX) and the glass-ceramic control group (PCG). Conventional resin cement combined with polymeric CAD/CAM inlays (TAC) ($p = 0.001 - 0.02$) as well as the negative control group (NCG) ($p = 0.001 - 0.047$) showed significantly lower marginal adaption. For the interface between resin cement and inlay marginal adaption, the polymeric inlays luted with conventional resin cement (TAC) was significantly inferior to the luted inlays using self-adhesive resin (TRX) ($p < 0.001$) and the positive control group (PCG) ($p < 0.001$). Among groups TAC and NCG, a negative impact of marginal adaptation after chewing simulation was observed. Figure 3 shows the SEM pictures of the marginal adaptation of each tested group.

3.2 Fracture load

Descriptive statistics (mean, SD, 95 % CI) of the measured fracture load of each experimental group are shown in Table 3. No significant differences of fracture load between the tested groups were found ($p > 0.05$). Group TAC showed the highest Weibull modulus ($m = 4.49$) and the PCG group the lowest ones ($m = 2.78$).

3.3 Failure types

Cracks of the restoration, of the tooth and cracks along the margin were discriminated from each other. Additionally we determined “cusp fractures” ending above, or so-called “severe fractures” extending below, the cemento-enamel junction. Cusp fractures and severe fractures were also included as tooth fractures, this did not exclude fractures of inlay or margin. Inlay fractures were less frequent for TAC compared to all other groups (Table 4). The most frequent fracturing of restorations was observed in the control groups NCG (direct-filled) and PCG (glass-ceramic inlays). Tooth cracks happened more frequently in groups TRX and TAC compared to the other groups. No significant differences for the cracks along the margin were found.

4. **Discussion**

This study was designed to assess how PMMA-based CAD/CAM fabricated inlays perform in large MOD cavities with respect to marginal adaptation and mechanical stabilisation of the restored tooth, when subjected to a chewing fatigue test and subsequent loading to fracture. The significant loss of marginal adaptation between dental hard tissues and the conventional resin adhesive system of the polymeric inlays and of resin-based direct filled restorations observed in the present study may be attributed to, on one hand, weakness of the adhesive system and, on the other hand, to elastic and thermal stresses as a result of the chewing fatigue testing. The loss of marginal adaptation after thermo-mechanical stressing of polymer-based restorations has also been observed in other studies [35, 36]. However, the present data show that the use of an effective and durable bond as established by the self-adhesive cement used in the group TRX prevented any significant loss of marginal adaptation. This may prove that the self-adhesive cement compensated for any stress exerted on the margins during chewing fatigue testing. Therefore, the first part of the null-hypothesis is rejected.

The results showed no significant differences between fracture loads of all groups, indicating that neither bonding system nor material, or the established quality of marginal adaptation had a significant effect. This might be different if cavity walls are even thinner than those used in this study. However, comparing the fracture load values obtained in the present study, from teeth restored with large inlays (896 - 1810 N) with those of unprepared molars (2156 ± 944 N), as obtained from an earlier study in our laboratory under similar conditions, the load resistance of the inlay-restored teeth appears rather low [37].

The results of the fracture analysis appear unrelated to the findings of marginal adaptation. While chewing fatigue caused similar poor marginal adaptation in both NGC and TAC groups, NCG showed inlay fractures in all specimens while TAC yielded zero. This corroborates that the quality of marginal adaptation was not at all related to any type of breakage under load. The polymeric CAD/CAM inlay groups demonstrated higher numbers of tooth fractures than PCG and NCG at similar fracture loads. The lower E-moduli of these materials seem to lower the stabilising effect of the restoration, compared to a ceramic inlay or direct composite filling [35]. This might limit the applicability of unfilled polymer inlays to narrow cavities.

Today, ceramic is the standard material for CAD/CAM inlay restorations. Clinical failure rate, aesthetic outcome and stabilisation of tooth substance are favourable for ceramics [16,17,40], whereas direct composite fillings exhibit lower marginal integrity in clinical practice and produce a lower stabilisation effect on remaining tooth substance [40,41]. Possible disadvantages of aesthetic silicate ceramic inlays are demonstrated by reports of breakage and chipping [40,41]. The fracture load values in the present study of PCG ceramic inlays are in accordance with the findings of these studies [40,41]. This explains the continued search for materials with higher fracture resistance.

Surface conditioning of polymeric CAD/CAM materials with air-abrasion prior to cementation yielded the highest tensile strength [6]. Therefore, the polymeric inlays in the present study were also air-abraded following the same protocol. The good results of marginal adaptation for the group TRX are comparable to findings from Frankenberger et al. 2011 [16]. However, another study showed low values of marginal adaptation of RelyX Unicem with tooth enamel [42]. This might be caused by the different curing methods of the cement, as this has a significant effect on shrinkage [43], and therefore leads to different qualities of marginal sealing.

Weibull statistics are considered appropriate to characterise the structural reliability of brittle dental materials [44-46]. A higher Weibull modulus indicates lower variability of strength, due to flaws and defects in the material [47,48]. In Weibull statistics, the characteristic strength (s) represents the 63.21 percentile of strength distribution [48,49]. In the present study, the fracture load data were supported with Weibull distribution, in which failure probability can be predicted at any level of stress. The software used (SPSS 19) allowed absolute estimates to be obtained, but information on the 95 % CI and the post-hoc test for Weibull parameters were not able to be calculated. Therefore, a Weibull statistical comparison between the tested groups has not been made. The adhesively luted glass-ceramic inlays showed the lowest Weibull modulus and the resin inlays TAC the highest.

In summary, based on the findings of marginal adaptation, fracture load and fracture analysis, unfilled PMMA CAD/CAM inlays luted with a self-adhesive resin cement may be applicable as long-term restorations in narrow cavities. Adequate occlusal wear stability of such materials should be further investigated in clinical studies.

5. Conclusions

Unfilled polymer CAD/CAM inlays luted with self-adhesive resin cement may be applicable as long-term restorations, provided that cavities are narrow.

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References

1. Mörmann WH. The evolution of the CEREC System. J Amer Dent Assoc 2006;137:7S-13S.
2. Mörmann WH. Composite inlay: research model with potential for practical use? Quintessenz 1982;33:1891-1900. [in German]
3. Otto T. Computer-aided direct ceramic restorations: a 10-year prospective clinical study of Cerec CAD/CAM inlays and onlays. Int J Prosthodont 2002;15:122-8.
4. Arnetzl G. Different ceramic technologies in a clinical long-term comparison. In: 243 Mörmann WH, ed. State of the art of CAD/CAM restorations: 20 years of CEREC. London: Quintessence 2006 pp.65-72.
5. Alt V, Hannig M, Wostmann B, Balkenhol M. Fracture strength of temporary fixed partial dentures: CAD/CAM versus directly fabricated restorations. Dent Mater 2011;27:339-347.
6. Stawarczyk B, Basler T, Ender A, Roos M, Özcan M, Hämmerle CHF. Effect of surface conditioning with air-abrasion on the tensile strength of polymeric CAD/CAM crowns luted with self-adhesive and conventional resin cements, J Prosthet Dent 2012;107:94.101.
7. Goncu Basaran E, Ayna E, Vallittu PK, Lassila LV. Load-bearing capacity of handmade and computer-aided design--computer-aided manufacturing-fabricated three-unit fixed dental prostheses of particulate filler composite. Acta Odontol Scand 2011;69;144-150.
8. Stawarczyk B, Ender A, Trottmann A, Özcan M, Fischer J, Hämmerle CHF. Load-bearing capacity of CAD/CAM milled polymeric three-unit fixed dental prostheses: Effect of aging regimens Clin Oral Investig 2012;16:1669-1677.

9. Cobankara FK, Unlu N, Cetin AR, Ozkan HB. The effect of different restoration techniques on the fracture resistance of endodontically-treated molars. Oper Dent 2008;33:526-533.
10. Magne P, Knezevic A. Thickness of CAD-CAM composite resin overlays influences fatigue resistance of endodontically treated premolars. Dent Mater 2009;25:1264-1268.
11. Magne P, Knezevic A. Simulated fatigue resistance of composite resin versus porcelain CAD/CAM overlay restorations on endodontically treated molars. Quintessence Int 2009;40:125-133.
12. Fasbinder DJ, Dennison JB, Heys DR, Lampe K. The clinical performance of CAD/CAM-generated composite inlays, J Am Dent Assoc 2005;136:1714-1723.
13. Lehmann F, Spiegl K, Eickemeyer G, Rammelsberg P. Adhesively luted, metal-free composite crowns after five years. J Adhes Dent 2009;11:493-498.
14. Stawarczyk B, Sener B, Trottmann A, Özcan M, Hämmerle CHF. Discoloration of manually polymerized resins and resin CAD/CAM blocks versus glass-ceramic: Effect of storage media, duration, and subsequent polishing. Dent Mater J 2012;31:377-383.
15. Krifka S, Anthofer T, Fritzsch M, Hiller KA, Schmalz G, Federlin M. Ceramic inlays and partial ceramic crowns: influence of remaining cusp wall thickness on the marginal integrity and enamel crack formation in vitro. Oper Dent 2009;34:32-42.
16. Frankenberger R, Kramer N, Appelt A, Lohbauer U, Naumann M, Roggendorf MJ. Chairside vs. labside ceramic inlays: effect of temporary restoration and adhesive luting on enamel cracks and marginal integrity. Dent Mater 2011;27:892-898.

17. Hannig C, Westphal C, Becker K, Attin T. Fracture resistance of endodontically treated maxillary premolars restored with CAD/CAM ceramic inlays. J Prosthet Dent 2005;94:342-349.
18. Krejci I, Reich T, Lutz F, Albertoni M. [An in vitro test procedure for evaluating dental restoration systems. 1. A computer-controlled mastication simulator]. Schweiz Monatsschr Zahnmed 1990;100:953-960. [in German]
19. Meyers MA, Chen PY, Lin AYM, Seki Y. Biological materials: structure and mechanical properties. Prog Mater Sci 2008;53:1-206.
20. Datzmann G. Cerec Vitablocs Mark II machinable ceramic. in: CAD/CIM in aesthetic dentistry; CEREC 10 Year Anniversary Symposium, Proceedings, ed Mörmann WH. Chicago: Quintessence 1996: pp 205-215.
21. Craig RG, Powers JM, Wataha JC. Dental materials, properties and manipulation 8th ed. St. Louis, Missouri: Mosby, 2004: pp 23-26.
22. Toparli M, Gokay N, Aksoy T. An investigation of temperature and stress distribution on a restored maxillary second premolar tooth using a threedimensional finite element method. J Oral Rehabil 2000;27:1077-1081.
23. He LH, Swain M. A novel polymer infiltrated ceramic dental material. Dent Mater 2011;27:527-534.
24. Behr M, Rosentritt M, Regnet T, Lang R, Handel G. Marginal adaptation in dentin of a self-adhesive universal resin cement compared with well-tried systems. Dent Mater 2004;20:191-197.
25. Oilo G. Bond strength testing-what does it mean? Int Dent J 1993;43:492-498.
26. Blatz MB, Sadan A, Maltezos C, Blatz U, Mercante D, Burgess JO. In vitro durability of the resin bond to feldspathic ceramics. Am J Dent 2004;17:169-172.

27. Behr M, Hansmann M, Rosentritt M, Handel G. Marginal adaptation of three self-adhesive resin cements vs. a well-tried adhesive luting agent. Clin Oral Investig 2009;13:459-464.
28. Roulet JF, Reich T, Blunck U, Noack M. Quantitative margin analysis in the scanning electron microscope. Scanning Microsc 3 1989 pp 147-158
29. Lutz F, Krejci I, Barbakow F. Quality and durability of marginal adaptation in bonded composite restorations. Dent Mater 1991;7:107-113.
30. International Organisation for Standardization. ISO 11405:2003. Dental materials - Testing of adhesion to tooth structure.
31. Krejci I, Lutz F, Boretti R. Resin composite polishing-filling the gaps. Quintessence Int 1999;30:490-495.
32. Gohring NT, Schonenberger KA, Lutz F. Potential of restorative systems with simplified adhesives: quantitative analysis of wear and marginal adaptation in vitro. Am J Dent 2003;16:275-282.
33. Stawarczyk B, Özcan M, Trottmann A, Hämmerle CHF, Roos M. Evaluation of flexural strength of hipped and presintered zirconia using different estimation methods of Weibull statistics. J Mech Behav Biomed Mater 2012;10:227-234.
34. Wissenschaftliche Tabellen Geigy, Teilband Statistik, Basel, 1980.
35. Schmidlin PR, Huber T, Göhring TN, Attin T, Bindl A. Effects of total and selective bonding on marginal adaptation and microleakage of Class I resin composite restorations in vitro. Oper Dent 2008; 33(6): 629-635.
36. Haller B, Trojanski A. Effect of multi-step dentin bonding systems and resin-modified glass ionomer cement liner on marginal quality of dentin-bonded resin composite Class II restorations. Clin Oral Investig 1998; 2(3):130-136.

37. Mörmann W, Wolf D, Ender A, Bindl A, Göhring T, Attin T. Effect of two-self-adhesive cements on maginal adaptation and strength of esthetic ceramic CAD/CAM molar crowns. J Prosthodont 2009;18:403-410.
38. Kelly JR, Benetti P, Rungruanganunt P, Della Bona A. The slippery slope – Clinical perspectives on in vitro research methodologies. Dent Mater 2012;41-51.
39. Mehl A, Kunzelmann KH, Folwaczny M, Hickel R. Stabilization effects of CAD/CAM ceramic restorations in extended MOD cavities. J Adhes Dent 2004;6:239-245.
40. Hitz T, Özcan M, Gohring TN. Marginal adaptation and fracture resistance of root-canal treated mandibular molars with intracoronal restorations: effect of thermocycling and mechanical loading. J Adhes Dent 2010;12:279-286.
41. Keshvad A, Hooshmand T, Asefzadeh F, Khalilinejad F, Alihemmati M, Van Noort R. Marginal Gap, Internal Fit, and Fracture Load of Leucite-Reinforced Ceramic Inlays Fabricated by CEREC inLab and Hot-Pressed Techniques. J Prosthodont 2011;20:535-540.
42. Ibarra G, Johnson GH, Geurtsen W, Vargas MA. Microleakage of porcelain veneer restorations bonded to enamel and dentin with a new self-adhesive resin-based dental cement. Dent Mater 2007;23:218-225.
43. Kitzmuller K, Graf A, Watts D, Schedle A. Setting kinetics and shrinkage of self-adhesive resin cements depend on cure-mode and temperature. Dent Mater 2011;27:544-551.
44. Quinn JB, Quinn GD. A practical and systematic review of Weibull statistics for reporting strengths of dental materials. Dent Mater 2010;26:135-147.

45. Chong KH, Chai J, Takahashi Y, Wozniak W. Flexural strength of In-Ceram alumina and In-Ceram zirconia core materials. Int J Prosthodont 2002;15:183-188.
46. Della Bona A, Anusavice KJ, DeHoff PH. Weibull analysis and flexural strength of hot-pressed core and veneered ceramic structures. Dent Mater 2003;19:662-669.
47. Quinn JB, Sundar V, Parry EE, Quinn GD. Comparison of edge chipping resistance of PFM and veneered zirconia specimens. Dent Mater 2010;26:13-20.
48. Stawarczyk B, Özcan M, Hämmerle CHF, Roos M. The fracture load and failure types of veneered anterior zirconia crowns: An analysis of normal and Weibull distribution of complete and censored date. Dent Mater 2012;28:478-487.
49. Weibull W. A statistical distribution function of wide applicability. J Appl Mechan 1951;18:293-297.

Tables

Table 1: Test groups, abbreviations, manufacturers and LOT-No. for all used materials.

Table 2: Mean, standard deviation and 95% confidential interval of marginal adaptation for both interfaces, separately.

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Figure 1: a) Guideline and dimensions (mm) of the preparation, b) Design of fracture load test, c) Fracture types: tooth fracture (1), inlay fracture (2), fracture along margin (3), cusp fracture (4), severe fracture (5).

Figure 2: Marginal adaptation of both interfaces (1: between dental hard tissues and luting resin cement, 2: between luting resin cement and CAD/CAM inlay) before and after aging

Figure 3: SEM pictures of marginal adaptation a) PCG, b) TRX, c) TAC, d) NCG.

Table 1: Test groups, abbreviations, manufacturers and LOT-No. for all used materials.

Groups	PCG	TRX	TAC	NCG
Type of re-construction	Glass-ceramic CAD/CAM, inlay	Unfilled polymer CAD/CAM inlay		Direct composite filling
Reconstruction material	Empress CAD (Ivoclar Vivadent, Schaan, Liechtenstein, LOT-No. L60040): Leucit reinforced glass ceramic	artBloc Temp (Merz Dental, Lütjenburg, Germany, LOT-No. 33908): PMMA-based resin without filler		Filtek Supreme (3M ESPE, Seefeld, Germany, LOT-No. 9YR): Nanofiller composite
Adhesion strategy (Tooth)	Phosphoric acid (Ultra-Etch, Ultradent Products INC, South Jordan, UT, USA, LOT-No. B6C6R) (30 s), Syntac Cassic (LOT-No. J28035/ J27820): Primer: TEGDMA, maleic acid. dimethacrylate, water adhesive: PEGDMA, maleic acid, glutaraldehyde, water Heliobond (LOT-No. G09457): Bis-GMA, dimethacrylate, initiators, stabilizers all: Ivoclar Vivadent Light curing (40 s)	Phosphoric acid (Ultradent Products INC) (enamel, 30 s),	Phosphoric acid (Ultradent Products INC) (enamel, 30 s) artCem ONE (Merz Dental, LOT-No. 5811037)	Phosphoric acid (Ultradent Products INC) (total etch, 15+30 s), Optibond FL (Kerr, Bioggio, Switzerland, LOT-No. 3204465/3215399): Primer: Hydroxyethylmethacrylat (HEMA), ethylalcohol, water Adhesive: Hydroxyethylmethacrylat (HEMA), Dinatrium-Hexafluorosilikat, Methacrylatester-Monomere, inerte Füller, water Light curing (40 s)

Adhesion strategy (Inlay)	4.9% Hydrofluoric acid (Vita Zahnfabrik, Bad Säckingen, Germany, LOT-No. 31160) Monobond S Heliobond	air-abrasion with alumina powder (50µm), LEMAT NT4, Wassermann, Hamburg, Germany		Incremental filling technique (8 increments) Light curing (8x30 s)
Cement	Variolink II (Ivoclar Vivadent, LOT-No. K41833/K39878): Bis-GMA, TEGDMA, UDMA, benzoylperoxide, inorganic fillers, ytterbium trifluoride, Ba-Al fluorosilicate glass, spheroid mixed oxide, initiator, stabilizers, pigments Light curing (300 s)	RelyX Unicem (3M ESPE, LOT-No. 352469):Powder: alkaline (basic) fillers, silanated fillers, peroxy components, pigments, substituted pyrimidine Liquid: methacrylate monomers containing phosphoric acid groups, acetate, initiators, stabilizers	artCem GI (Merz Dental, LOT-No. 7806520): Powder: barium-aluminum-silicate glass, nano-fluorapatite, pigments, initiator Liquid: polyacid, methacrlylate , initiator 2-hydroxyethylmeth-acrylate, dimethacrylate, initiator, stabilizers	

Table 2: Mean, standard deviation and 95% confidential interval of marginal adaptation for both interfaces, separately.

	Initial				After chewing fatigue test			
	Interface 1		Interface 2		Interface 1		Interface 2	
Group	Mean (SD)	95% CI	Mean (SD)	95% CI	Mean (SD)	95% CI	Mean (SD)	95% CI
PCG	98.1 (0.8)^{AB}	(97.2;99.0)	98.2 (0.8)^{A}	(97.2;100)	93.2 (3.1)^{A}	(89.8;96.6)	95.1 (2.9)^{A}	(92.1;98.2)
TRX	98.7 (0.5)^{A}	(98.1;99.3)	98.8 (0.5)^{A}	(95.9;99.8)	95.1 (1.6)^{A}	(93.3;96.8)	93.5 (3.6)^{A}	(89.5;97.3)
TAC	91.1 (3.9)^{C}	(87.0;95.2)	91.0 (2.4)^{B}	(89.2;94.3)	76.0 (5.2)^{B}	(70.4;81.5)	81.3 (4.7)^{B}	(76.2;86.2)
NCG	93.6 (3.5)^{BC}	(89.8;97.3)	-		72.3 (8.0)^{B}	(63.7;80.8)	-	

Table 3: Descriptive statistics (mean (SD)), 95% confidence intervals and Weibull statistic of measured fracture load (N).

Group	Mean (SD)	95% CI	Weibull modulus	Characteristic value
PCG	1160 (412)^{A}	(896;1422)	2.78	1312
TRX	1470 (536)^{A}	(1128;1810)	2.82	1658
TAC	1219 (267)^{A}	(1048;1389)	4.49	1333
NCG	1160 (294)^{A}	(971;1347)	4.05	1279

Table 4: Fracture types.

	A	B	C	D	E
PCG	9	6	4	5	1
TRX	4	12	7	6	4
TAC	0	11	6	10	1
NCG	12	7	1	6	2

A: Fracture of restoration
B: Tooth fracture
C: Fracture along the margin
D: Cusp fractures that require a reparation with a crown or an overlay
E: Severe fractures that extend beneath the cemento-enamel junction
One tooth contains at least one of criteria A, B or C but can contain all combinations of them.
Criteria D and E are additional if applicable.

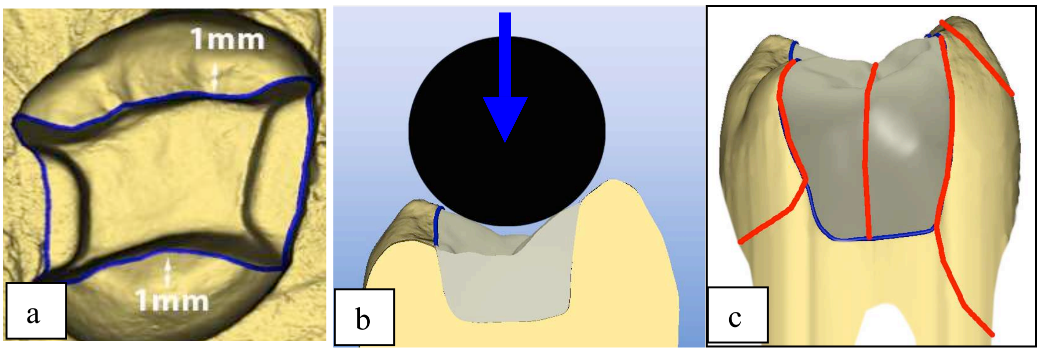

Figure 1: a) Cavosurface margin line and its distance from the occlusal ridge line (mm).
b) Configuration of the fracture load test. c) Fracture types: tooth fracture (1), Inlay fracture (2), fracture along margin (3), cusp fracture (4), severe fracture (5).

Figure 2: Marginal adaptation of both interfaces (1: between dental hard tissue and luting resin cement, 2: between luting resin cement and CAD/CAM inlay) before and after chewing fatigue test.

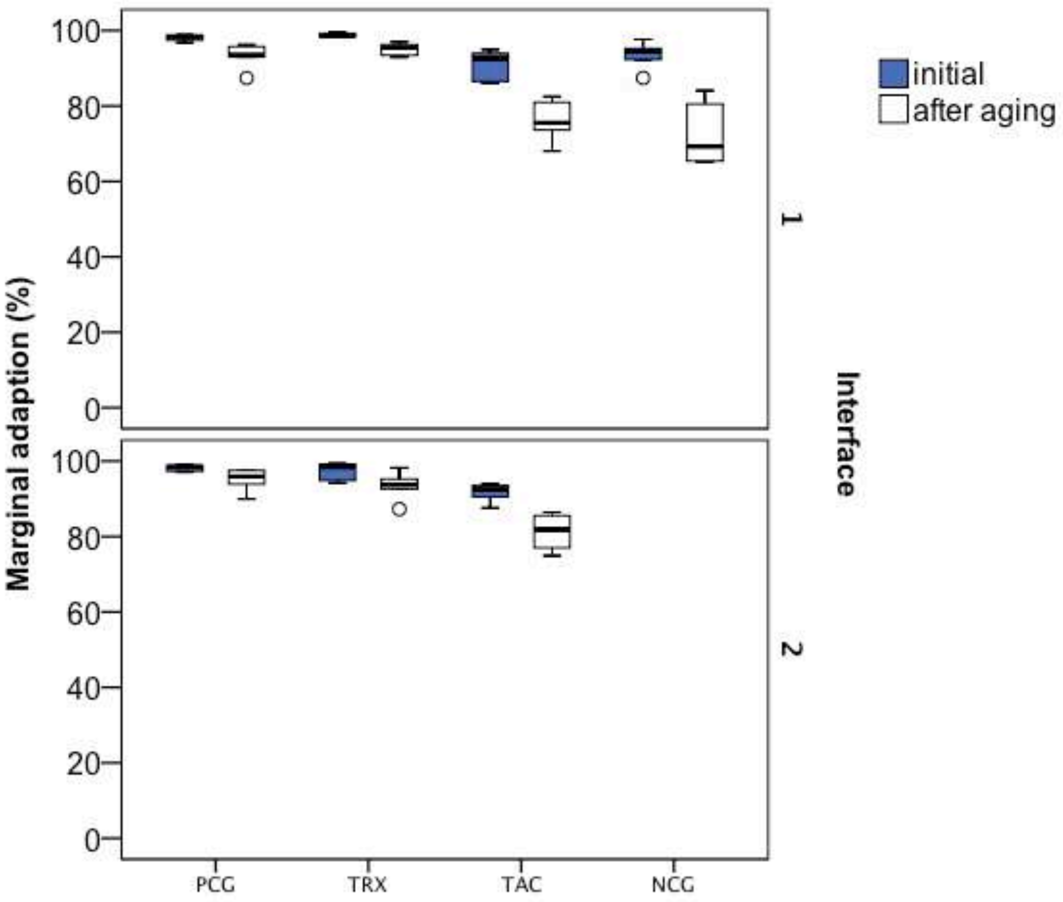

Figure 3: SEM pictures of marginal adaptation a) PCG, b) TRX, c) TAC, d) NCG.